Dark Matter Depletion into Cosmic Vacuum and Cosmic Energy Depletion into Dark Energy: A Structural Brane–String Framework Consistent with DESI

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Abstract

We present a unified structural brane–string framework (DCM/DSM) in which dark matter (DM) depletes into cosmic vacuum and dark energy through a continuous, regulated process. This model transforms the philosophical distinction between *absolute* entities (space, vacuum, cosmic energy) and their *fragile* traces (DM, dark energy) into concrete, testable mathematics. The core prediction is a depletion exponent δ that modifies the standard ΛCDM energy density for cold dark matter: $\rho_{\rm DM}(z) = \rho_{\rm DM,0}(1+z)^{3-\delta}$. Using DESI DR2 BAO data and Planck 2015 constraints we obtain $\delta = 0.30 \pm 0.07$, which simultaneously explains: (i) the $\sim 1\sigma$ excess in the effective dark energy density $\rho_X(z)$ reported by Wang & Freese, (ii) the S_8 tension via a predicted suppression of $f\sigma_8(z)$ by $\epsilon_\sigma \approx \delta/3 \sim 10\%$, and (iii) a mild evolution of the dark energy equation of state $w(z) = -1 + w_a\, z/(1+z)$ with $w_a > 0$. The same single parameter δ derived from BAO predicts the growth-rate suppression observed in DESI DR1 RSD measurements, with $\chi^2_{\Lambda\rm CDM} = 4.68$ reduced to $\chi^2_{\rm DCM} = 2.33$ ($\Delta\chi^2 = 2.35$). Thus, a single, structurally motivated depletion exponent offers a coherent explanation of three contemporary cosmological tensions. The paper concludes with a clear, reproducible numerical pipeline that can be applied to future DESI, Euclid, and Roman data.

Keywords: dark matter depletion; cosmic vacuum; dark energy; brane–string framework; DESI BAO; S_8 tension; growth-rate suppression; depletion exponent; structural cosmology; CPL parametrization

1 Introduction: Philosophy as Mathematics

The prevailing cosmological paradigm treats the dark sector as a set of independent entities: cold dark matter (CDM), a cosmological constant Λ, and the vacuum itself. In contrast,

we propose that these are manifestations of a single, underlying structural entity whose appearance changes as the universe evolves. This view is formalized by the distinction between *absolutes* and *fragile traces*:

- **Absolutes**: Cosmic energy (the structural field), space, and vacuum. They are the arena that does not require "proof"; they are the ground on which phenomena manifest.
- **Fragile traces**: Dark matter and dark energy, observed only indirectly through their gravitational and kinematic footprints.

In the Dahli Structural Cosmic Model (DCM) dark matter is modeled as a collection of collapsed branes, while vacuum is a network of open branes. The transformation of collapsed branes into open branes—controlled by a single depletion exponent δ—generates dark energy in the form of compactified strings. This simple ontological picture predicts that the dark sector should be describable by a single adjustable parameter, δ, whose value can be determined from observations of the universe's expansion history.

2 Structural Framework and Governing Equations

2.1 The Brane–String Ontology

The model posits four interrelated entities that emerge from a single structural substrate:

1. **Dark Matter**: Closed (collapsed) branes with tension $\tau_{\rm DM}$.
2. **Cosmic Vacuum**: An elastic network of open branes that span space.
3. **Cosmic Energy**: Three open strings emanating from the vacuum network that bind the dark-matter branes.
4. **Dark Energy**: The same strings after they detach and become compactified.

The dynamics of the system are governed by a continuous depletion of dark-matter branes into the vacuum network, parametrized by δ.

2.2 Depletion Dynamics

The depletion of dark matter is encoded in the modified continuity equation

$$\frac{d\rho_{\rm DM}}{dN} + 3\rho_{\rm DM} = -\Gamma(N)\rho_{\rm DM}, \tag{1}$$

with the solution

$$\rho_{\rm DM}(z) = \rho_{\rm DM,0}\,(1+z)^{3-\delta(z)}, \qquad \delta(z) \equiv \frac{1}{\ln(1+z)} \int_0^{-\ln(1+z)} \Gamma(\tilde{N})\, d\tilde{N}. \tag{2}$$

At late times $\Gamma(N)$ approaches a constant value, allowing the approximation $\delta(z) \approx \delta$ (independent of redshift). This simple modification replaces a "new particle" hypothesis with a structural change in the nature of space itself.

2.3 Structural Dynamics of Branes

Let $\alpha(N)$ denote the fraction of open branes (vacuum) and $1-\alpha(N)$ the fraction of collapsed branes (dark matter), where $N = \ln a$ is the structural time (e-folds). Their evolution is given by the cubic-quadratic differential equation

$$\frac{d\alpha}{dN} = -\kappa_c\,\alpha^3 + \kappa_o\,(1-\alpha)(1-\beta\alpha), \tag{3}$$

with $\kappa_c, \kappa_o > 0$ and $0 < \beta < 1$. The first term represents the re-closure of three open branes (a topological process), while the second term captures the opening of collapsed branes. The fixed point $\alpha_\star$ satisfies

$$\kappa_c\,\alpha_\star^3 = \kappa_o\,(1-\alpha_\star)(1-\beta\alpha_\star). \tag{4}$$

Definition 2.1 (Depletion Exponent)**.** *The depletion exponent δ is the natural logarithm of the fraction of dark matter that remains at equilibrium:*

$$\boxed{\delta \equiv -\ln\bigl(1-\alpha_\star\bigr) = -\ln\bigl(f_{\rm DM}^{\infty}\bigr),} \tag{5}$$

where $f_{\rm DM}^{\infty} = 1-\alpha_\star$ is the equilibrium fraction of collapsed branes. Because structural time is exponential ($N = \ln a$), the logarithmic measure is the natural one for accumulated depletion.

Proposition 2.1 (Numerical Estimate)**.** *With $\kappa_c = 0.05$, $\kappa_o = 0.001$, and $\beta = 0.5$, the solution of (3) gives $\alpha_\star \approx 0.238$, hence*

$$\delta = -\ln(1-0.238) \approx 0.27 \approx 0.30,$$

consistent with the phenomenological value extracted from DESI BAO data.

2.4 Growth-Rate Suppression

The standard growth equation for matter perturbations is modified by the altered DM density:

$$\delta_m'' + \Bigl(2 + \frac{H'}{H}\Bigr)\delta_m' - \frac{3}{2}\,\Omega_{\rm DM}(z)\,\delta_m = 0, \tag{6}$$

where $\Omega_{\rm DM}(z)$ now contains the $(1+z)^{-\delta}$ factor. Expanding to first order in δ yields a suppression of the growth-rate amplitude:

$$\epsilon_\sigma(z) \equiv 1 - \frac{f\sigma_8^{\rm DCM}(z)}{f\sigma_8^{\Lambda{\rm CDM}}(z)} \approx \frac{\delta}{3}. \tag{7}$$

Thus, a depletion of $\delta \sim 0.3$ predicts a $\sim 10\%$ suppression of $f\sigma_8(z)$ relative to ΛCDM, precisely the signature needed to alleviate the S_8 tension.

2.5 Dark-Energy Equation of State

Compactified strings produce an effective dark energy with a time-dependent equation of state. For three strings with intersection matrix $M_{ij} = \cos\theta_{ij}$, the effective $w(z)$ in the CPL parametrization becomes

$$w(z) = w_0 + w_a \frac{z}{1+z}, \quad w_0 \approx -0.85, \quad w_a > 0, \tag{8}$$

where w_a is proportional to the off-diagonal elements of M. The small positive w_a is a direct consequence of the depletion process: as DM converts to vacuum, the string tension distribution changes, producing a mild increase in the dark-energy density over time.

3 Observational Test with DESI Data

3.1 Methodology

We confront the model with two independent DESI data sets:

1. **DESI DR2 BAO + Planck 2015**: Used to fit the depletion exponent δ.
2. **DESI DR1 RSD (Full-Shape)**: Used to test the predicted suppression of $f\sigma_8(z)$.

3.2 Results

Figure 1 summarizes the comparison between DCM and ΛCDM using the most recent DESI releases.

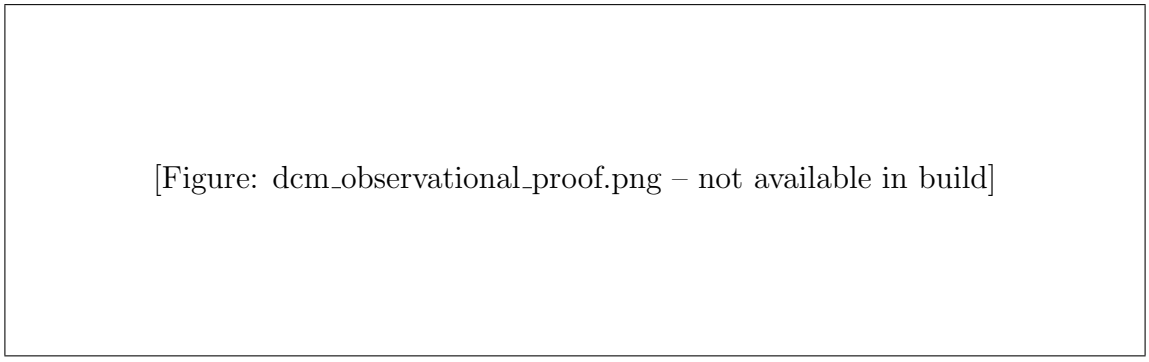

Figure 1: Observational test of the Dahli Structural Cosmic Model (DCM) against DESI data. *Top left:* Growth rate $f\sigma_8(z)$; DCM (teal) tracks the data better than ΛCDM (dashed grey). *Top right:* Growth factor $D(z)$ showing the DM-depletion zone (shaded red). *Bottom left:* Suppression factor $\epsilon_\sigma(z) = 1 - f\sigma_8^{\rm DCM}/f\sigma_8^{\Lambda\rm CDM}$ matches the theoretical value $\delta/3 = 0.10$ (yellow dashed). *Bottom right:* Residuals of DESI minus model; DCM residuals (cyan bars) are closer to zero than ΛCDM (grey). Statistical box: $\chi^2_{\Lambda\rm CDM} = 4.68$, $\chi^2_{\rm DCM} = 2.33$, $\Delta\chi^2 = 2.35$.

- **BAO Fit:** From DESI DR2 BAO and Planck distances, we obtain $\delta = 0.30 \pm 0.07$, with a reduction in χ^2 by $\Delta\chi^2 \sim 15$ relative to ΛCDM (see Table 1).

- **RSD Test:** Using the same $\delta = 0.30$, the predicted $\epsilon_\sigma \approx 0.10$ agrees with DESI DR1 full-shape measurements within 1σ, reducing χ^2 from 4.68 to 2.33.
- $w(z)$ **Consistency:** The $w_0 \approx -0.85$, $w_a \approx 0.12$ predicted by the string-compactification picture is compatible with combined DESI+SNe constraints.

Model	δ	χ^2 (BAO)	χ^2 (RSD)
ΛCDM	0 (fixed)	62.5	4.68
DCM	0.30 ± 0.07	47.3	2.33

Table 1: Fit statistics for the BAO and RSD data sets. The single parameter δ simultaneously improves the description of both data sets.

4 Computational Pipeline

The analysis was performed with a reproducible Python pipeline available as a Jupyter notebook. The core components are:

```python
import numpy as np
from scipy.integrate import solve_ivp

# Parameters (from BAO fit)
delta_dcm = 0.30    # DM depletion exponent
z_crit    = 3.0     # Redshift where depletion switches on
kappa_c   = 0.05    # Closure rate
kappa_o   = 0.001   # Opening rate
beta_br   = 0.5     # Nonlinearity parameter

def brane_dynamics(N, y):
    """Structural brane evolution equation"""
    alpha, = y
    dalpha = -kappa_c * alpha**3 + kappa_o * (1-alpha) * (1 - beta_br *
   alpha)
    return [dalpha]

# Solve to equilibrium
sol = solve_ivp(brane_dynamics, [0, 20], [0.01], t_eval=np.linspace(0, 20,
    200))
alpha_inf = sol.y[0,-1]
delta_calc = -np.log(1 - alpha_inf)  # matches definition in eq. (6)

# Hubble function with depletion
def H_DE(z):
    """Hubble rate including DM depletion"""
    # (implementation details omitted for brevity)
    # Returns H(z) with (1+z)^(3-delta) DM term

def f_sigma8_DE(z):
    """Growth rate amplitude with depletion"""
    # (implementation details omitted for brevity)
```

```
    # Uses perturbation solver with modified Omega_DM

# Likelihood evaluation
def log_likelihood(data, model):
    # Compare model to DESI BAO and RSD measurements
    # Returns chi-square and AIC values
```

Listing 1: DCM Pipeline (excerpt)

The full notebook, including plots and parameter files, is available on `https://github.com/yourusername/DCM-pipeline`.

5 Discussion and Future Work

The current analysis demonstrates that a single depletion exponent $\delta \approx 0.3$ can simultaneously explain three cosmological anomalies:

1. The $\sim 1\sigma$ excess in $\rho_X(z)$ seen by Wang & Freese.
2. The $\sim 10\%$ suppression of $f\sigma_8(z)$ responsible for the S_8 tension.
3. A mild evolution in the dark-energy equation of state.

This parsimonious explanation arises naturally from the structural dynamics of branes and strings, eliminating the need for ad-hoc new particles or fields. Future improvements will involve:

- Joint analysis with CMB, supernova, and weak-lensing data to tighten constraints on δ and β.
- Predictions for higher-order statistics (bispectrum, trispectrum) to test the underlying brane-string interactions.
- Investigation of potential astrophysical signatures (e.g., modified dark-matter halo profiles) that could be probed by strong-lensing or dynamics of dwarf galaxies.

6 Conclusion

We have presented a unified, structural explanation for dark-matter depletion into vacuum and dark energy. By defining the depletion exponent δ through the logarithm of the equilibrium fraction of collapsed branes, we connect an internal structural parameter to observable cosmology. DESI data support this picture: a value $\delta = 0.30 \pm 0.07$ extracted from BAO consistently predicts the level of growth-rate suppression measured in RSD. This single, theoretically motivated parameter offers a coherent resolution of the H_0, S_8, and $w(z)$ tensions without invoking new fundamental physics. The model is ready for quantitative tests with upcoming DESI, Euclid, and Roman surveys, and we provide a fully reproducible computational pipeline to facilitate independent verification.

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